Sensor Head
Component Specification

David Headland

9 December 2002

Contents

1 Original System

Since this project is attempting to meet or exceed the performance of a previously designed system, the specifications of the original system must be determined in order to check that requirements are being met.

1.1 Light source

The light source used in the original system was a Hamamatsu L2690 890nm LED. Light from this device was passed through a Melles Griot SELFOC gradient index lens and into an Ensign-Bickford HCPM 1000 T-10 optical fibre.

1.1.1 LED

The Hamamatsu L2690 LED has the following characteristics:

- 890nm wavelength light output
- 14mW radiant optical flux (at 50mA current)
- 1.45V forward voltage (at 50mA current)
- 0.4×0.4mm square emission size
- Non-reflective packaging
- 0.28dB optical power output change per 10°C temperature change

1.1.2 Optical fibre and lens

Information on the exact optical fire used, which is described as "HCPM 1000 T-10, NA=0.37, Ensign-Bickford Optics Company, USA" is difficult to obtain. It is stated in the report that a 1mm diameter fibre was used, indicating that a 50/125 or 62.5/125 fibre would have been sued as these types often have an outside diameter of 1mm.

The light generated by the LED is passed through a 0.25 pitch Selfoc lens to increase the collimation. This is a gradient index lens that in a perfect example with perfect coupling will focus collimated light onto a point source right at the edge of the lens.

Similar lenses are built into the packages of a number of commercially available LEDs. For these devices, the angular distribution of the light emitted from the device is around 10-15°.

1.2 Light detector

The light returning from the skin was passed along a similar optical fibre as was used in the source. This was coupled to a Newport Corporation 835 optical power meter. This product is now discontinued, and little information is available about its specifications.

As a comparison, the specifications for the similar Newport 819-IR optical power meter have been included in the component specification comparison tables in section 2 on page 16.

2 Sensor head arrangement

The blood vessel mapping method used by this project requires that a collimated beam of light is projected onto the skin. the reflected light is then detected by a device a known distance away.

The separation distance determines the effective depth at which the device will be scanning for blood vessels, so, the separation of the light source and detector needs to be adjustable to be able to scan for blood vessels at different depths.

This is the only external requirement placed on the sensor head itself. Any method can be used to guide and position the light before it comes into contact with the skin. Some possible arrangements are discussed below.

2.1 Direct positioning

The light source and the detectors are positioned directly above the skin surface. The beam created by the light source assembly is projected directly onto the surface, and the reflected light is measured directly. This is the simplest arrangement, providing benefits in the form of low costs and reduced sensor head complexity.

The main problem with this approach is getting the source and detector close enough to each other to allow shallow scanning depths. We would been the source and detector to be as close as 2mm from each other for the most shallow scans.

Another potential problem with this approach is connection to the rest of the scanning system. At the very least, wires must run from the controlling circuitry to the light source and detector, which will have to move about in the Earth's magnetic field as the head moves. An estimate of the noise EMF induced this way can be calculated:

$$\begin{aligned} B &= \frac{\Phi}{A} \\ \varepsilon &= \frac{d\Phi}{dt} \\ \varepsilon &= \frac{d(BA)}{dt} \end{aligned}$$

Where:

B	Earth's magnetic field strength, approximately 50μT
Φ	Magnetic flux

A	Area bounding the moving wire
t	time to move across one scan line, approximate 1s
ε	Induced noise EMF (V)

If we assume that the head will be moving at a constant velocity, and that 50cm wires are used for connection, and remain perpendicular to the Earth's magnetic field, we can calculate the approximate induced noise EMF based on a 3cm scan line as follows:

$$\begin{aligned} \varepsilon &= \frac{\Delta(BA)}{\Delta t} \\ \varepsilon &= \frac{50 \times 10^{-6} \times 0.5 \times 0.03}{1} \\ \varepsilon &= 7.5 \times 10^{-7} \end{aligned}$$

Giving an approximate amplitude for magnetically induced noise of 0.75μV. In the case of a phototransistor or an integrated photodiode and amplifier circuit, changes in light level of even 1mW/cm^2 would provide an output changes of significantly greater than 0.75μV. However, photodiode current changes would be much smaller, meaning that their signals could get lost in the noise generated by the environmental magnetic field.

2.1.1 Laser diode direct positioning

If a laser diode is to be used as the light source, the light output from the device would be collimated very well, allowing the device to be positioned further away from the skin than for an LED whilst still achieving acceptable collimation at the scanning site.

This allows by laser beam to be shone close to the edge of the detector's packaging, allowing for closer positioning of the source and detected beams. It does not, however, eliminate the problem of electromagnetic noise or the large, heavy packaging of a laser diode module.

2.2 Optical fibre positioning

It would be possible to locate the light source and detector in a location separate from the scanner head itself, and use optical fibres to guide the light to and from the head assembly. Since there are no electrical conductors being moved around, no EMF will be induced my moving the optical fibres.

In order to be able to position the centre of the source and the detector 2mm away from each other, and without using a laser diode, some form of guidance such as optical fibres must be used because of the size of the packages of the source and detector components.

2.3 Mirror positioning

Collimated beams of light could be reflected off a rotating mirror onto the source and back again. This allows the source and detector positions to remain constant, reducing electromagnetic noise without using optical fibres.

This approach, however, requires the mirror to be rotated through two axes, which would be a difficult task to achieve, especially within the accuracy and precision bounds required by this project. Using a single mirror approach will also alter the angle of incidence of the light beam onto the skin, which should remain constant for the whole scan.

The latter problem could be resolved by using an array of two or more mirrors moving as a system to reposition the beam. The complexities involved with moving the mirrors are likely to take quite some time to work around, rendering this idea impractical in the given time scale.

3 Losses

3.1 Light loss positions

3.1.1 At the scanning site

The main loss of power will be between the end of the light guidance system from the source, absorption in and under the skin and in the atmosphere between the skin and the detection light guidance system. If we assume no losses between the light source and the detector apart from at the scanning site, we can estimate the maximum optical power to be detected.

If absorption in the skin is ignored, we can consider all the power incident upon the skin to be available to be detected. As the light gets scattered, however, it will radiate in all directions. This can be modelled as a point source of light on the surface of the skin.

Optical power will dissipate in an approximately spherical manner. The output power will be spread across the surface area of this virtual sphere, which will have a curved surface. For simplicity, if a section of the surface area of a sphere is considered to be flat, at any point away from the point source the optical power will be:

$$P_d = \frac{P_s A_d}{4\pi r^2}$$

Where:

P_d	Detectable power per unit area at the point in question (W/m^2)
r	Distance from the virtual point source (m)
P_s	Power dissipated by the point source (W)
A_d	Detection area (m^3)

This relationship is illustrated graphically in figure 1 on the next page.

For example, if the light source was emitting 7mW of optical power, and the detector was positioned mm away from the surface of the skin, the detectable optical power would be approximately:

$$\begin{aligned} P_d &= \frac{7 \times 10^{-3} A_d}{4\pi \times (2 \times 10^{-3})^2} \\ P_d &= 139 A_d \end{aligned}$$

Which is a power per unit area of 139W/m^2. Taking a photosensitive device with a circular photosensitive area of 1mm diameter, A_d and therefore the maximum power at the detector can be calculated:

$$\begin{aligned} A_d &= 2.5\pi \times 10^{-7} \\ P_d &= 139 \times 2.5\pi \times 10^{-7} \\ P_d &= 1.09 \times 10^{-4} \end{aligned}$$

So for this arrangement, the optical power at the detector will be about 0.109mW, 1.56% of the power of the source.

3.1.2 Light guidance

The above assumptions will give a maximum optical power at the detector assuming the only loss is at the scanning site. This would be an acceptable model if the source and detector were to be directly positioned on the head close to the scanning site.

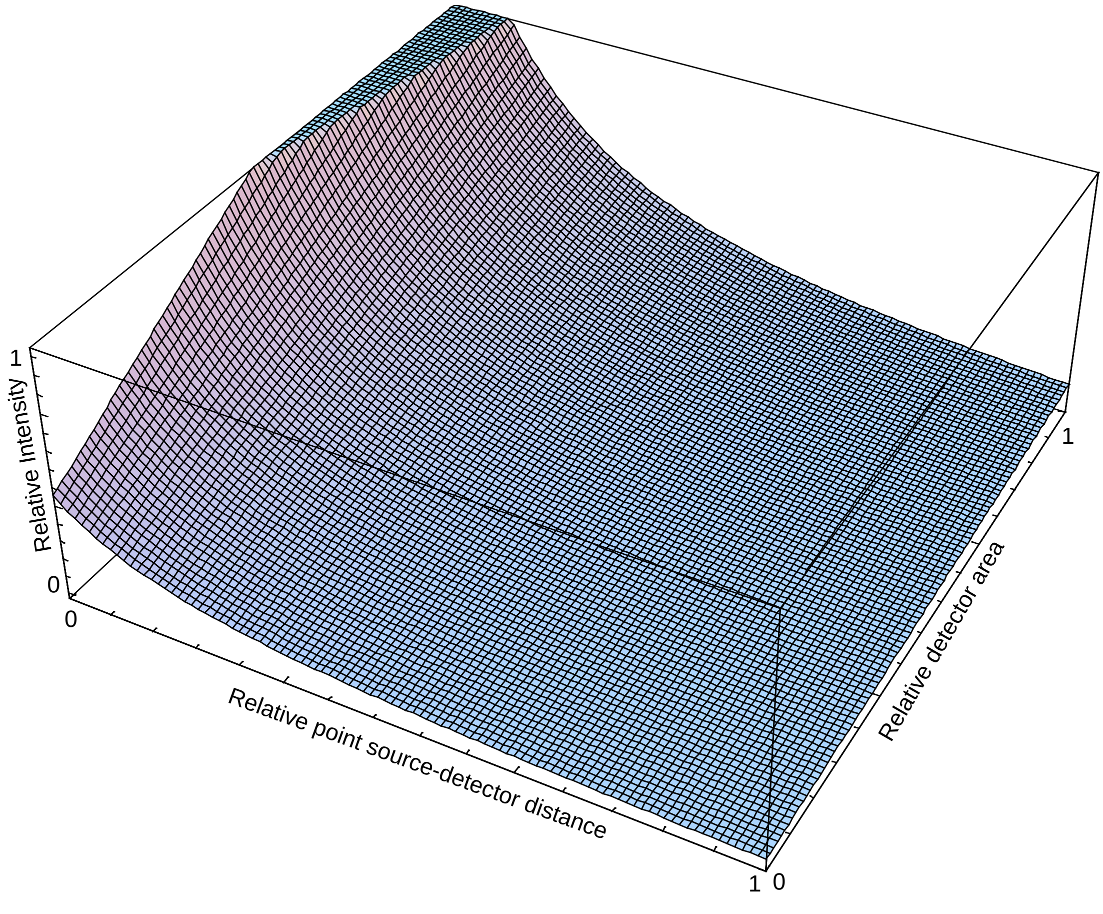

Figure 1: Light loss graphical illustration

The effect of light dispersion along an optical fibre is to reduce the bandwidth of the fibre. Scanning a line of 100 data points is expected to take around 1-2 seconds, giving a worst case scanning frequency of 100Hz. Because optical fibres have a bandwidth-distance product of hundreds of thousands of MHz.km, dispersions in the fibres can be considered negligible in this case.

Assuming optical fibres are used to guide the light from the source to the scanning site and then back to the detector, the attenuation of the fibre must be taken into account. In the near infrared region, attenuation in an average optical fibre will be in the order of 1-2dB/km. For this system, the fibres would need to be longer longer than about a metre, leading to very small losses in light power from the attenuation of the optical fibres.

The main loss in optical fibres will be at the ends of the fibres as the refractive index of the material the light is travelling through changes. A typical loss due to reflection and refractive index change would be about 0.6dB, allowing approximately 85% of the optical power to pass.

3.2 Optical power levels

3.2.1 Direct positioning

With direct positioning, the point source model will give an upper bound for the optical power level to be detected at the photosensitive element. As calculated in section 3.1.1 on page 7, the relationship between power at the detector, power at the source, area of the detector and distance from the point source to the detector can be modelled as:

$$P_d = \frac{P_s A_d}{4\pi r^2}$$

If the optical power emitted by the source is constant, within the bounds of this simplified model the optical power incident on the detector will increase linearly with the area of the detector, and decrease linearly with the square of the distance the detector is positioned from the source.

For a typical detector with a circular 1mm diameter area, it was shown that about 6.25% of the optical power emitted from the source would be present at the detection area. For a typical light source providing 7mW of optical power, this would cause a maximum of 0.437mW of power to be incident on the detector.

For this component arrangement on the sensor head, I would recommend a detector with a 140W/m^2 dynamic range

3.2.2 Light guidance

If optical fibres are used to give the light from the source to the scanning site, then from the scanning site to the detector, additional losses will occur at the boundary between each stage, as indicated by the diagram below:

$$\begin{tikzcd}[row sep=small]
\text{Light source} \arrow[d, "{[1]}"] \\
\text{Source guidance fibre} \arrow[d, "{[2]}"] \\
\text{Scanning site} \arrow[d, "{[3,4]}"] \\
\text{Detection fibre} \arrow[d, "{[5]}"] \\
\text{Light detector}
\end{tikzcd}$$

The losses at each transition can be summarised as follows:

1. Reflection and loss on light entering the source optical fibre (85% transmission efficiency)
2. Reflection and loss on light leaving the source optical fibre (85% transmission efficiency)
3. Light dispersion at the scanning site as described in section 3.2.1 on the page before (6.25% transmission efficiency)
4. Reflection and loss on light entering the detection optical fibre (85% transmission efficiency)
5. Reflection and loss on light leaving the detection optical fibre (85% transmission efficiency)

This can be modelled as for the direct positioning system, but with an adjusted power output at the point source. The power of the detector would have to be multiplied by 0.85^4 to account for losses at the ends of the optical fibres. This would allow us to estimate:

$$P_d = \frac{0.52 P_s A_d}{4\pi r^2}$$

If we assume a typical components as for the direct positioning arrangement, ie a light source emitting 7mW of optical power as for the direct positioning system and an optical fibre placed 2mm away from the scanning site, we can say:

$$\begin{aligned} P_d &= \frac{0.52 \times 7 \times 10^{-3} \times A_d}{4\pi \times (2 \times 10^{-3})^2} \\ P_d &= 72A_d \end{aligned}$$

Based on these calculations, and types of components, I would recommend a detector with a 75W/m^2 dynamic range

4 Device considerations

4.1 Light source

4.1.1 Choices

Many different light sources are available, however the system requires close to monochromatic light in either the red, near infrared or infrared wavelengths. Two type of light source seem suitable for this application at first glance:

- LEDs
- Laser diodes

Both devices will produce light of a narrow wavelength range, with the laser providing a narrower output wavelength range than the LED.

4.1.2 Collimated output

A major concern for the light source is obtaining a collimated beam. With most commercially available laser diode modules, the output light beam spreads at a very narrow angle, generally less than 1°. LEDs, however, can be modelled as emitting light in all directions.

Various manufacturers produce LEDs with lenses built into the package to produce a beam with a spread angle of 10-15°. This should provide a similar level of collimation to adding a 0.25 pitch Selfoc lens to the outside package of an LED. I have so far been unable to find find devices with highly collimated output, so if a more collimated beam is required an external lens will be required.

Using a spherical lens with a focal length equal to the distance between an LED and the end of its package would cause all light emitted from the LED through the lens to be collimated, assuming the light was emitted from a clearly defined point source.

Since an LED emits light in all directions, many packages reflect light to point towards the front of the device to maximise light output. This would affect the focusing if an external lens were to be used. LEDs are available in non-reflective packages, such as the Hamamatsu L2690 as used in the original experiment. This would greatly restrict the effective light source, allowing the lens to more accurately collimate the beam.

Collimating lenses are available for standard laser diode modules with a cost that is generally only slightly higher than that of a stand alone lens that would have to be used for LEDs.

4.1.3 Output power

The original paper suggested that the intensity of light emitted at the source had little bearing on the percentage change of light intensity at the detector, so exact matching should not be required, making either an LED or laser diode suitable light sources.

It would be interesting to look at the effectiveness of the system based on incident light power in the experiment. This would require a method of limiting the output power of the source device in the circuitry for the sensor head, but could be easily implemented for either an LED or laser diode using current limiting resistors.

Even if there is no time to investigate the effects of different optical power inputs, a stable optical power output would be important, so a stable current source would be required as the supply to the light source device.

4.1.4 Packaging

If the device is to be directly mounted onto the scanning head, it must be small and light enough so as to not impair the function of the overall system. The scanning unit itself will use precision actuators for the positioning of the head, so the head must be small and light enough that inertia does not cause a problem for the actuators.

LEDs are available in a variety of sizes and generally weigh very little. Laser diode modules and normally packaged in much larger containers, and weight considerable more than LEDs.

4.2 Light detector

4.2.1 Possibilities

There are many light detectors commercially available. Major groups are:

- Light dependant resistors
- Photodiodes
- Phototransistors
- CCD arrays
- Photovoltaic cells

As mentioned in the feasibility report, light dependant resistors and photovoltaic cells are not particularly suitable for very sensitive applications such as this. They tend to be quite non-linear and slow to respond to environmental changes.

CCD arrays at a basic level are arrays of photodiodes or photo MOS capacitors. Since we are only looking at a single column of light that is being diffused through the skin, an array of detectors is unnecessary.

Photodiodes are normally put in circuits reverse biased, so under normal conditions negligible current would flow through the diode. However, the PN junction of the diode is exposed, and light falling on the junction will cause carriers to move into the conduction band, allowing larger currents to flow through the device.

Phototransistors work in a similar manner to photodiodes, except the base of a bipolar transistor is exposed to light. This affects the current flowing through the base of the transistor, which is amplified as for a 'normal' transistor to allow a current to flow from collector to emitter.

In terms of general device characteristics, photodiodes and phototransistors seem suitable for this application, and will be investigated further.

4.2.2 Thermal stability

Almost all electronic devices change their characteristics along with their temperature. Since all electronics create heat, even controlling the ambient temperature will not completely eliminate this problem.

In many circuits, thermal changes are not a major concern. However, since the aim of the sensor head is to look for some very small changes against a much larger background field, thermal changes could conceivably be interpreted as a signal.

This problem is particularly important for the light detector. Any errors introduced here will be amplified in later stages, and could easily drown out the wanted signal. It is therefore necessary to use components with particularly stable thermal characteristics.

4.2.3 Drive requirements

The unit will be outputting to a voltage-based analogue to digital converter. Ideally, such a device should have an infinite input impedance, but in practice a an input impedance of at least 10MΩ can be expected. At 10V, this would give a current of 10^{-5}A, which all light detection devices should be able to source.

Because of the small variations in signal, it is proposed that the signal from the light detector is amplified, with respect to an adjustable reference voltage. This would effectively allow the signal to be extracted from the background field.

A side effect of such an arrangement is the low output impedance of an operational amplifier, which should be able to drive much higher loads. As mentioned above, this is not a significant factor for this particular project, but may be useful if the scanning head is ever used with different controlling and load hardware.

4.2.4 Device types

Phototransistors would be particularly suited to low light level situations, as the current generated by the light would be amplified to more usable levels. The background light level for this application will be relatively high, which the changes in light level being important. Because of this, a photodiode would probably be more useful than a phototransistor.

Photodiode devices are available in integrated circuits containing integral amplifiers. This approach should reduce the overall system complexity. Noise picked up by external or PCB track runs will be reduced, and the number of voltage drops from interconnections will decrease.

Table 1: Light source specification comparison

Parameter	Hamamatsu L2690	Honeywell SE5470	Sharp GL514	Vector 785nm LD	DeHarpporte Red LD	Unit
Angular distribution	10	10	7	0.3	0.5	°
Aperture	1.0	3.4	3.0	4.5	—	mm
Wavelength	890	880	950	785	650	nm
Power output	14	7.0	3.31	3.0	<5	mW
Thermal stability	-0.028	-0.040	-0.040	-0.015	—	dB/K
Package diameter	4.2	4.1	4.7	15	12	mm
Unit cost	—	3.16	3.73	131.58	19	£

5 Device specifications

5.1 Light source

The characteristics of some possible light source devices are summarised in table 1.

5.2 Light detector

The characteristics of some possible light detection devices are summarised in table 2 on the next page.

6 Recommendation

6.1 Physical arrangement

Section 2 on page 4 gives details of some different positionings for the active components on the scanning head. The two most practical arrangements were the direct positioning and the light guidance by optical fibre arrangements.

Table 2: Light detector specification comparison

Parameter	Newport 818-IR Power Meter	Sharp PT510	Honeywell SD5443	Burr Brown OPT301	IPL 10530 DAL	Unit
Thermal stability	0.1	0.5	0.5	0.02	1.0	%/K
Sensitivity	±2%	2mA.cm^2/mW	—	0.24A/W	60V/μW/mm^2	—
Dynamic range	3	10	5	0.5-15	—	mW/cm^2
Acceptance angle	90	6	10	40	10	°
Peak wavelength	850-1700	800	870	770	950	nm
Package diameter	3.0	4.7	4.8	9.4	8.3	mm
Unit cost	518	3.88	1.45	20.60	17.70	£

The main problem with the direct positioning method is allowing the centre of the light source and the detector to get close enough to each other. To meet the specification of the original system, the centres of the active areas need to be as close as 2mm to each other.

The smallest source device package has a diameter of 4.1mm, and the detector (apart from the Newport power meter which is not acceptable for this project) is 4.8mm. This gives a centre-centre separation of 4.5mm as a minimum, without considering the need for shielding the devices to stop light leaking directly from the source to the detector.

Without using moving mirrors which would create a lot of extra complexity, the other option is to position the source and detector components away from the scanning head. Light could then be guided to and from the head using optical fibres.

This option creates the problem of having to couple the fibres to the light source and detector. Devices are available commercially to couple active optoelectronic devices and optical fibres, such as the Sweet Spot dry non-polished system, but only for a limited range of devices.

Coupling an arbitrary device to a fibre could be achieved by taking a block of solid material, for example a rigid plastic, and drilling a hole with a diameter equal to that of the device part of the way in to the block. If the hole diameter was then changed to the diameter of the fibre to continue the drilling, the device and fibre could be held in close contact. A small amount of glue at the holder interface would prevent the devices working their way loose.

In order to minimise weight and physical complexity at the scanning head, the simplest approach for holding the fibres would be to take a sheet of a material such as acrylic and drill a variety of holes into it. The source fibre could be fixed in one hole, and the detector fibre moved through the others to change the effective scan depth.

6.2 Light source

The model provided in section 3.1.1 on page 7 shows that for a typical arrangement using optical fibres to guide the time between the source, the scanning site and the detector, an optical power density of around 72W/m^2 would be present as a maximum at the detector. The detectors shown in table 2 on the preceding page have dynamic ranges of between 0.5 and 15W/m^2.

It has also been sown in section 3.1.1 that several factors influence the power at the detector (assuming all others factors remain constant):

- The detector power is directly proportional to the detector area (area of the optical fibre in this case).
- The detector power is directly proportional to the source power.
- The detector power is inversely proportional to the square of the distance between the detector fibre and the scanning site.

The easiest way to reduce the power levels at the detector would be to reduce the source power levels. The original experiment found that the percentage change in power levels at the detector was approximately constant as the incident power was varied, so adjusting the power output of the source should not affect the sensitivity or range of the system.

An typical laser diode from RS is listed in table 2 on page 16 which has excellent specifications for this application, but the price makes it prohibitive. A cheaper laser diode module is also listed, but specifications on the device are unavailable. It appears to be a device pool, as the suppliers cannot even guarantee who will manufacture the module.

The remaining possibilities are the NIR LEDs. Using one of the devices with a built-in lens would solve the problem of attaching a lens at the appropriate position with respect to the LED, simplifying the connection to the source optical fibre.

This leave a choice between the Sharp and Honeywell LEDs, both of which are similarly specified. For scanning efficiency, I would recommend the use of the Honeywell LED, as it has an output wavelength closer to that of the blood vessels to be mapped, which should increase the absorption when scanning over the blood vessels.

6.3 Light detector

Of the devices shown in table 2 on page 16, the Newport power meter is unacceptable for this project because of the high cost of the unit. It is listed as a reference for the other components, as it is similar to the power meter used in the original system.

Little information is available form the manufacturer or suppliers about the IPL 10530 DAL integrated photodiode and amplifier. Since we are looking for components to meet a reasonably tight specification, this renders the component unsuitable.

Of the remaining components, I would recommend the Burr Brown OPT301 integrated photodiode and amplifier. It offers 2.5 times the temperature stability of the other remaining devices, and has a dynamic range adjustable by way of a resistor, which can be tuned to account for oversimplifications in the design of the models in section 3.

Using this combination of components, assuming a the environmental temperature could change by 2° during scanning, the power at the detector could change by 1.82%. combined with a detector temperature stability of 0.02%, this could lead to a 1.84% error due to local short-term changes in thermal conditions, for which an 8-bit A-D converter would be quite acceptable.